SUBMILLIMETER,FAR-INFRARED SPECTROSCOPY OF THE INTERSTELLAR MEDIUM

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ABSTRACT.

Spectroscopic studies of interstellar clouds can now be made in the submillimeter and far-infrared bands, essentially free from the absorbing effects of the Earth's atmosphere, by means of the NASA Kuiper Airborne Observatory. Also large telescopes for the submillimeter are now under construction on mountain tops. Both high and intermediate resolution spectroscopic techniques have been successfully employed in the detection of many new molecular and atomic lines including rotational transitions of hydrides such as OH, H_2O, NH_3, and HCl; high J rotational transitions of CO; and the ground state fine structure transitions of atomic carbon, oxygen, singly ionized carbon and doubly ionized oxygen and nitrogen. In addition, heavy molecules have prolific spectra in the near millimeter band, and this is expected to extend to the submillimeter. These various submillimeter transitions have been used to study the physics and chemistry of clouds throughout the galaxy, in the galactic center region, and in neighboring galaxies.

INTRODUCTION

This paper is a somewhat expanded version of a review paper given at the Kuiper Airborne Observatory anniversary earlier this summer.

The parts of the electromagnetic spectrum known as the submillimeter and far-infrared are among the few remaining bands where there is limited astronomical information available. The reason is, of course, that the Earth's atmosphere is sufficiently opaque to prevent studies from the ground except for certain spectroscopic windows, which are available only from high mountains. As a result, the technology has not been developed, and only now is a large effort being mounted for detectors and telescopes. Anticipated projects include the Caltech 10.4 m telescope for Mauna Kea, Hawaii, the UK/Netherlands 15 m telescope for the same mountain, the German/Arizona 10 m telescope for an Arizona mountain, and the ESO 15 m telescope for Chile. Some of the new facilities will be available as soon as 1986 or 1987. A major factor in allowing astronomers a view of the submillimeter and the far-infrared has been the Kuiper Airborne Observatory (KAO). Even though the 91.5 cm telescope is small for use at long wavelengths, the availability of a telescope carried above the tropopause has proved of enormous utility. It is expected that this success will eventually lead to a major space facility for the submillimeter/far-infrared, currently known as the Large Deployable Reflector (LDR).

In this brief review only spectroscopic studies of interstellar gas will be discussed. Of course, a very large body of work exists for continuum studies in the submillimeter and far-infrared. It has been most exciting to find with the KAO that, not only are the species present in the interstellar medium, which were expected to provide useful spectra, but their abundance and distribution sometimes are much greater than anticipated. The information obtained will be invaluable in designing future space missions, such as LDR. Furthermore, ground-based studies of molecular emission features in the one-millimeter band indicate a very high density of heavy molecule lines, which will be even more pronounced in the submillimeter.

Spectroscopic features in the submillimeter and far-infrared are expected to be dominated by molecular rotational lines (Townes, 1957) and by atomic fine structure lines (Petrosian, 1970). We may be fairly confident that the interstellar medium is comparably rich in the submillimeter band to stellar atmospheres in the optical band. From the results of millimeterwave spectroscopy, we know that the interstellar medium contains many molecular species, but it is important to note that the typical temperature of the gas is 10 - 100K, which means that most of the energy emitted by the medium will be in the range 1mm - 100μm, roughly speaking. The small telescope of the KAO is excellent for identifying molecular and atomic species when they are reasonably widespread in the gas. However, the molecular species H_2O and O_2 are still largely inaccessible even from the KAO because the atmosphere is highly absorbing in the very same lines which are strong in the interstellar medium. In some cases, for relatively weak telluric lines, sufficient velocity shift is available for galactic clouds to allow a line detection.

Most of the available spectroscopic transitions in the submillimeter and far-infrared fall into three categories.

(1) Light Molecules

These molecules contain hydrogen, incorporated into the structure in such a way that the lowest rotational modes are dominated by the hydrogen mass, so that the lowest frequency appears in the submillimeter. For most of the simple hydride molecules, this is the case, and they can only easily be observed in the submillimeter. The study of the metal hydrides should lead to an improved understanding of interstellar chemistry and could be used to trace the abundance of metals through the galaxy.

(2) Heavy Molecules

Although heavy molecules possess transitions which can be observed in the millimeter band, it is most helpful to an understanding of the physics of the gas to have available the higher energy transitions for comparison. In fact, for the low dipole moment molecule CO, which dominates the energy balance for some clouds, it is necessary to observe as many lines as possible to determine the temperature, density and velocities of the cloud as a function of depth through the cloud. Whereas CO lines may be important cloud cooling lines, other higher dipole moment molecules provide better information on high-density knots within the clouds.

Interstellar medium chemistry has made great progress with the introduction of ion-molecule reaction schemes (Herbst and Klemperer, 1973). The amazing complexity of the interstellar medium spectrum is continuing to constrain the chemical models and cause even major revisions in the basic scheme. The sample spectrum shown below indicates the wealth of information for analysis of the chemical and physical properties of the clouds.

(3) Atoms

Atoms or atomic ions may possess a ground state with a net orbital electronic angular momentum, so that the state may be split by spin-orbit effects. Several of the light atoms have a ground state fine structure of this kind, which provides transitions in the submillimeter and far-infrared. With increasing atomic weight, the transitions move rapidly into the infrared and optical. In general it would be expected that the atomic gas would be a distinct phase of the interstellar medium as compared with the dense molecular gas. Observations of these transitions in the submillimeter from the KAO may be indicating that this is not always the case and that atomic species permeate the dense gas, requiring a major modification to the chemistry schemes (see Langer et al, 1984, and below). High spatial and spectral resolution data will be of very great importance here.

Several transitions of carbon, oxygen, ionized carbon, doubly ionized oxygen and nitrogen have been detected and used for studies of the galaxy and nearby galaxies. These studies are already stimulating new discussions of the atomic constituents of diffuse and dense clouds.

INSTRUMENTS

Various types of spectroscopic instruments have been employed in the submillimeter and far-infrared, many of which have been developed in conjunction with the KAO telescope. Basically there are two types of spectrometer in use. For very high spectral resolutions ($\delta\nu/\nu \lesssim 10^{-4}$), heterodyne spectrometers have been used, for intermediate resolutions ($\delta\nu/\nu \gtrsim 10^{-4}$) Fabry-Perot or grating spectrometers have been chosen. If the performance of heterodyne and direct detectors is compared, the regimes in which one outperforms the other can be established. An analysis of a specific telescope configuration has been made by Phillips and Watson (1984) in the LDR Science Coordination Group report on Focal Plane Instruments. For a 200K telescope with .05 emissivity, heterodyne detectors with quantum efficiencies of 0.1 are compared with direct detectors with NEP's of 10^{-16} Watts $Hz^{-\frac{1}{2}}$. Figure 1 indicates this comparison over the submillimeter and far-infrared bands. The break at 200μm is due to the availability of photodetectors (<200μm) which do not suffer from detector noise. The assumptions used to derive Figure 1 are close to the situation for the KAO telescope, but for the new mountain top telescopes the background will often be much greater, which further emphasizes heterodyne spectroscopy. The practical situation in which heterodyne spectroscopy is dominant at long wavelengths and high resolution ($\delta\nu/\nu$) and direct spectroscopy at short wavelengths and low resolution is seen to be unavoidable with current technology and for warm telescopes or high sky backgrounds.

To the present date the heterodyne instrumentation has consisted of a InSb heterodyne bolometer operating between 1.3 mm and 450μm (Phillips and Jefferts, 1973), with noise temperatures varying from about 100K to 400K through the range, but with a restricted bandpass (1-2 MHz), and Schottky diode receivers (see Kelley and Wrixon, 1980, for a recent review, or Erickson, 1978), whose noise temperatures are typically a factor of 10 higher, but do not suffer a bandwidth limitation, in principle. A more recent development has been the SIS receiver, which makes use of single quasiparticle tunneling between superconducting electrodes. These devices have proved very low noise in the millimeter band (see reviews by Phillips and Woody, 1982, and Kollberg, 1982) and have great promise for the submillimeter (Sutton, 1983). Direct spectroscopy has been performed with a cooled Fabry-Perot and a cooled grating, both operating between 160 and 50μm.

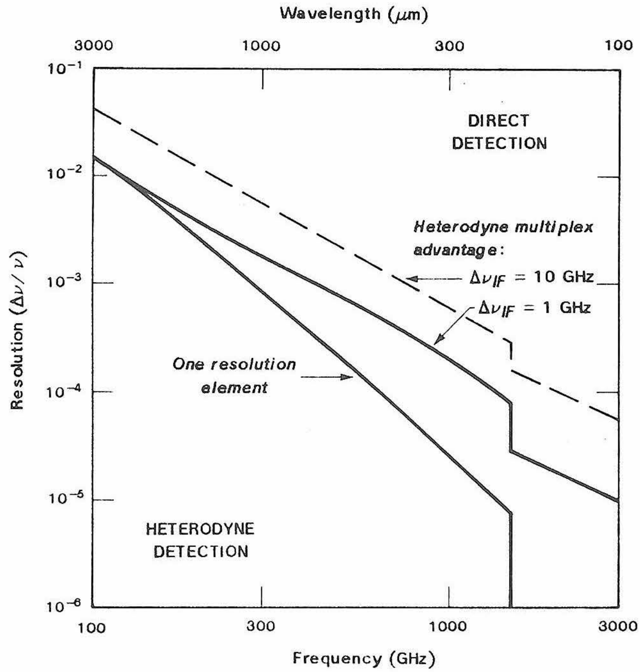

Figure 1. Relative sensitivity of heterodyne and direct detection.

SPECTROSCOPY OF LIGHT MOLECULES (AND CO)

Table 1 gives a list of most of the light molecule lines detected in the submillimeter and far-infrared. Most of these were found using the KAO. The activity has been somewhat of a pioneering nature so that only strong lines (or lines which were thought to be strong) appear in the list. As sensitivities and spectroscopic resolution improve, a host of lines will be available for study.

Table 1

Submillimeter and Far-Infrared Molecular Lines

Species	Transition	Wavelength	Reference
H_2O	3_{13} - 2_{20}	1,640μm	Waters *et al.* (1980)
	4_{14} - 3_{21}	789μm	Phillips, Kwan, and Huggins (1980)
OH	$^2\Pi_{3/2}$ (J=5/2 - 3/2)	119μm	Storey, Watson, andTownes (1981)
	$^2\Pi_{3/2}$ (J=7/2 - 5/2)	85μm	Watson *et al.* (1984)a
	$^2\Pi_{1/2}$ (J=3/2 - 1/2)	163μm	Genzel *et al.* (1985)
NH_3	$J_K = 1_0 - 0_0$	524μm	Keene, Blake, and Phillips (1983)
	$J_K = 4_3 - 3_3$	125μm	Townes *et al.* (1983)
HCl	J = 1-0	479μm	Blake, Keene, and Phillips (1984)
CO	J = 3-2	870μm	Phillips *et al.* (1977)
	J = 4-3	652μm	Phillips, Kwan, and Huggins (1980)
	J = 6-5	433μm	Goldsmith *et al.* (1981)
	J = 16-15	163μm	Stacey *et al.* (1983)a
	J = 17-16	153μm	Stacey *et al.* (1982)
	J = 21-20	124μm	Watson *et al.* (1980)
	J = 22-21	119μm	Watson *et al.* (1980)
	J = 26-25	100μm	Watson *et al.* (1984)a
	J = 27-26	97μm	Storey *et al.* (1981)
	J = 30-29	87μm	Storey *et al.* (1981)
	J = 31-30	84μm	Watson *et al.* (1984)a
	J = 34-33	77μm	Watson *et al.* (1984)a

(1) H_2O

The first molecular detection from the KAO was that of the 3_{13}-2_{20} transition of water by Waters et al. (1980) at 1,640μm. Normally, the atmosphere prevents the study of interstellar water, except via the high lying 6-5 masing transition. However, the 3_{13}-2_{20} transition is of somewhat low line strength and can be observed through the atmosphere from KAO altitdues. This important detection was from the Orion Molecular cloud core region. Some further information was obtained on the water abundance from the 4_{14}-3_{21} transition at 790μm by Phillips, Kwan, and Huggins (1980). This line is stronger in the atmosphere and so the observations were made when the maximum velocity shift of Orion relative to the Earth occurred. From the line strengths and lineshapes observed, e.g. see Figure 2, it was deduced that the H_2O emission was from the shocked region of the cloud and that the formation of H_2O gas in the interstellar medium may be related to shock activity.

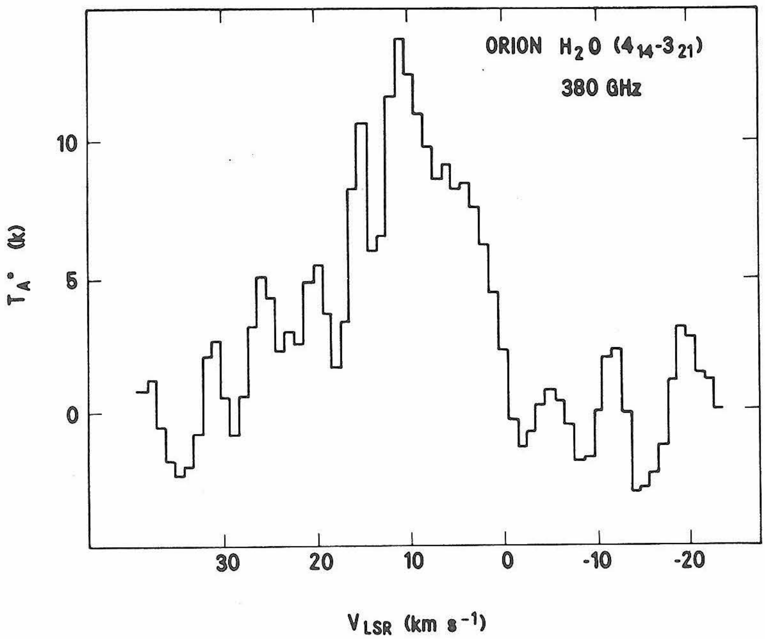

Figure 2

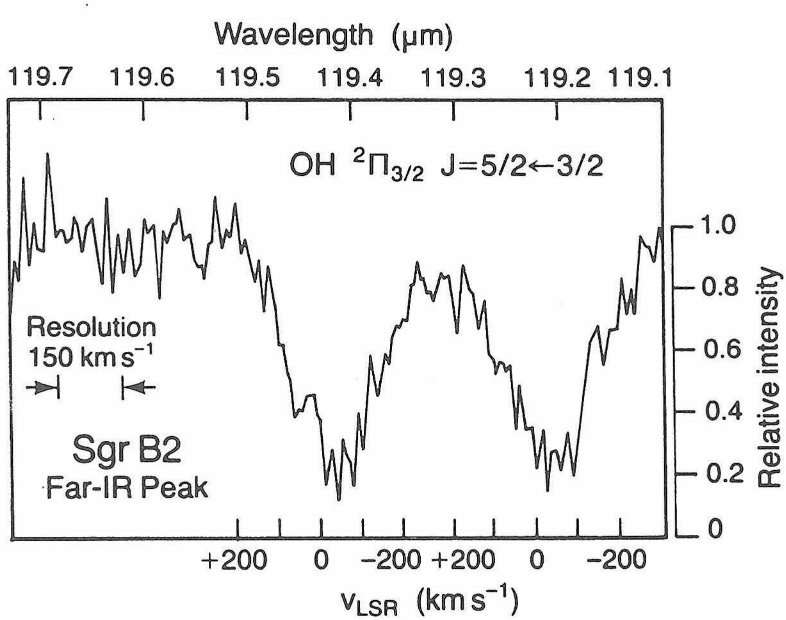

Figure 3

(2) OH

OH is easily observed by means of its Λ doubling radio lines, but the fundamental rotational transitions occur at 119μm for the $^2\Pi_{\frac{3}{2}}$ ladder and at 163μm for the $^2\Pi_{\frac{1}{2}}$ ladder. These have been detected from KAO. Figure 3 shows the spectrum of OH $^2\Pi_{\frac{3}{2}}$ (J = 5/2-3/2) observed in absorption towards Sgr B2 (Storey, Watson and Townes, 1981).

(3) NH_3

Ammonia is also easily observed in the radio by means of its inversion doubling lines, but again the fundamental rotation transitions lie in the submillimeter and far-infrared. Two of the rotation lines have recently been observed, the $J_K = 1_0\text{-}0_0$ transition was observed with the InSb heterodyne bolometer (Keene, Blake, and Phillips, 1983) and therefore shows the necessary spectral resolution to determine the line shape and central velocity. The observations were of the core of the Orion Molecular Cloud and indicated that the NH_3 emission originated mostly from the dense quiescent cloud at V_{LSR} = 9 km/sec, but with a large optical depth. The spectrum is shown in Figure 4. The $4_3\text{-}3_3$ emission detected by Townes et al. (1983) is thought to be emanating from the 'hot core', which is a dense hot region near the cloud center with a V_{LSR} of about 5 km/sec. It is most encouraging that information on the ground states of one molecule can be obtained with such disparate techniques and wavelengths.

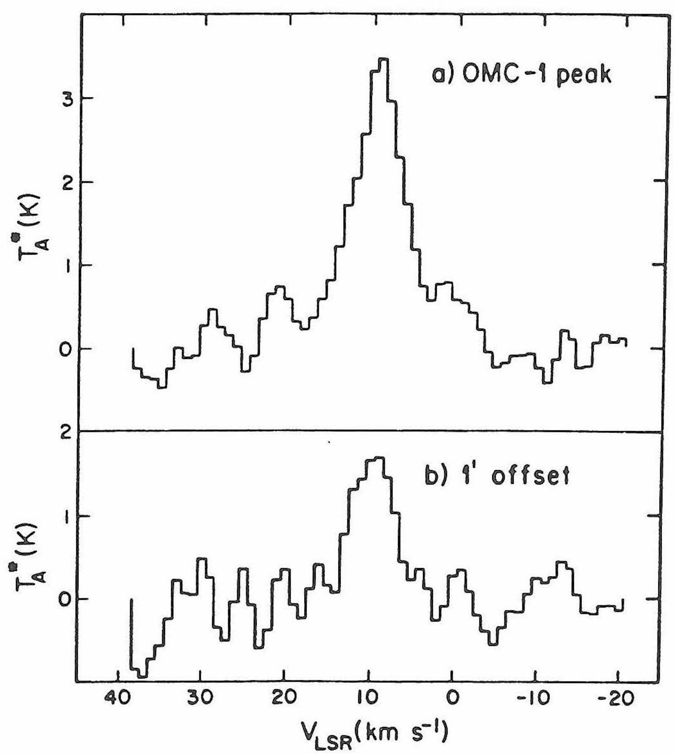

Figure 4

(4) HCl

A goal of submillimeterwave spectroscopy in the interstellar medium has been to establish to viability of the use of the metal hydride rotational spectra for astronomy. Many of the simple hydrides presumably can only be observed in the submillimeter, at least in dense clouds, so the technique is vital for monitoring the abundances of the metal hydrides and therefore of the metals themselves, in the gas of the galaxy. It is exciting to report the detection of HCl (Blake, Keene and Phillips, 1984) as the first of the 'metal' hydrides to be detected in this way, and incidentally representing the first detection of chlorine in interstellar molecules.

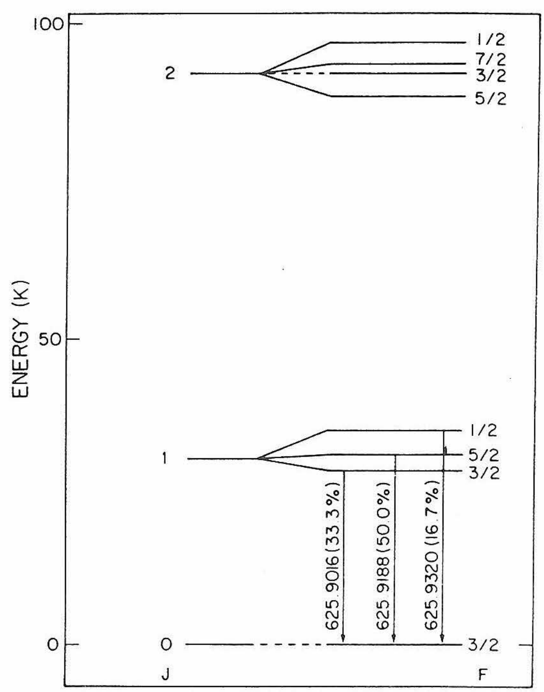

Figure 5. Energy level diagram for HCl.

Figure 5 shows the energy level diagram for the low lying states of the $H^{35}Cl$ molecule. Fortunately the molecule possesses a nuclear spin and concomitant hyperfine structure, so that there are three lines which can be resolved in heterodyne spectroscopy in the ground J = 1-0 transition. This is a vital aid to identification, for although the line frequencies are accurately determined by laboratory spectroscopy, the interstellar medium possesses many weak lines due to excited states of complex molecules. Figure 6 shows the KAO observed spectrum at 479μm, again in the direction of the core of the Orion Molecular Cloud. The expected line positions and relative strengths are indicated by the vertical lines. From these data it has been tentatively deduced that the order of 10% of the interstellar chlorine is in the HCl molecules.

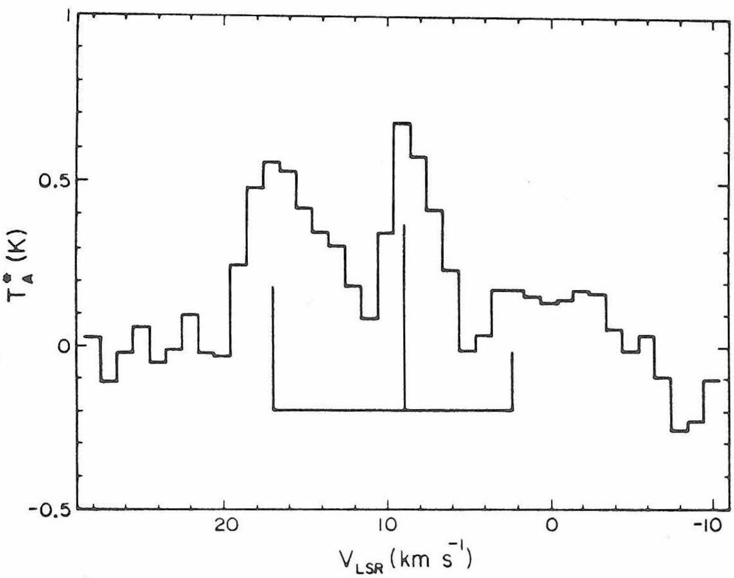

Figure 6. HCl J = 1-0

(5) CO

From studies at millimeter wavelengths of the low J rotational transitions of CO it is known that this molecule is the most abundant (apart from H_2) in the interstellar medium and that it is responsible for about 1/3 of the flux in the millimeter band from molecules. It is most important to have available as many of the CO transitions as possible, to obtain the best possible picture of the physics of the clouds and to compute the molecular cooling.

Table 1 gives the list of CO lines observed. The J = 3-2 and J = 4-3 transition were first observed with the Caltech InSb heterodyne spectrometer. The J = 6-5 transition with the U. Mass/Goddard Schottky receiver. The J = 16-15 and J = 17-16 with the Cornell grating and all the others with the Berkeley Fabry-Perot. The spectra for Orion are similar, except that the heterodyne data reveal the separation between the 'spike' feature due to quiescent gas and the underlying 'plateau' feature due to the shocked gas. A typical Fabry-Perot spectrum (J = 34-33) is shown in Figure 7. Watson et al. (1984) have been able to model the CO emission from shocked gas in Orion as due to a 750K source of density 2.7 x 10^6 cm^{-3}.

Heterodyne submillimeter studies of the lower J CO lines carried out from UKIRT by White (1982) give an indication of the great utility of this type of spectroscopy.

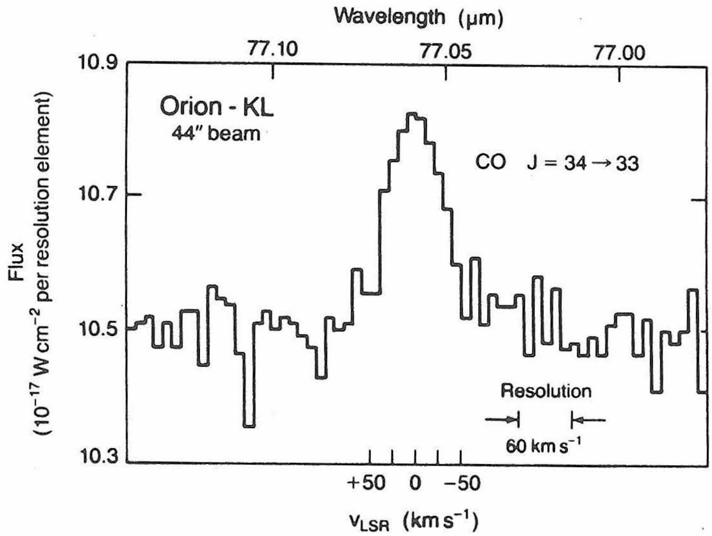

Figure 7

PECTROSCOPY OF HEAVY MOLECULES

Several submillimeter studies have been carried out for specific eavy molecules, such as that for HCN (White, 1982), but it has not been ossible yet to make a systematic evaluation of the frequency of occurence f high J molecular lines in the submillimeter. Some work in this direction as been started at the Millimeter Wave Observatory of Texas where several igh J lines of heavy molecules have been detected. Probably, the best ndication is to be obtained from the equivalent 1 mm studies of Sutton t al. (1984 and 1985). Figure 8 shows a high resolution spectrum of the requency range 215-265 GHz towards the OMC-1 cloud core. The spectrum s amazingly rich, consisting of more than 500 lines (counted very onservatively). The line frequency is so high that Sutton et al. were ble to conclude that the line flux contributed to the order of one half f the observed (apparent) OMC-1 continuum emission at this wavelength.

Also, somewhat surprisingly, nearly all of the observed lines in this pectrum could be accounted for in terms of the spectra of about 30 heavy olecules and ions, after the quantum mechanical calculations and laboratory pectroscopy studies had been carefully carried out (Blake et al., 1985). able 2 lists the molecules and lines assignment numbers.

TABLE 2

CO	^{13}C, ^{17}O, ^{18}O	4
CN		12
CS	^{13}C, ^{33}S, ^{34}S	4
SO	^{34}S	7
SIO		1
SIS ?		1

PN ?		1
OCS	^{13}C, ^{34}S	8
HCN	D	1
HNC	D	1
HCS^+		1
H_2O	D	1
H_2S		1
SO_2	^{34}S	38
H_2CO	D, ^{13}C	7
H_2CS		8
HNCO		11
HC_3N		11
CH_3CN	^{13}C	50
HCOOH		8
H_2CCO		10
CH_3OH	^{13}C	66
CH_3CHO ?		4
CH_3CCH		8
C_2H_3CN		37
HCO_2CH_3		134
$(CH_3)_2O$		20
C_2H_5CN		83
		538
U-LINES		23

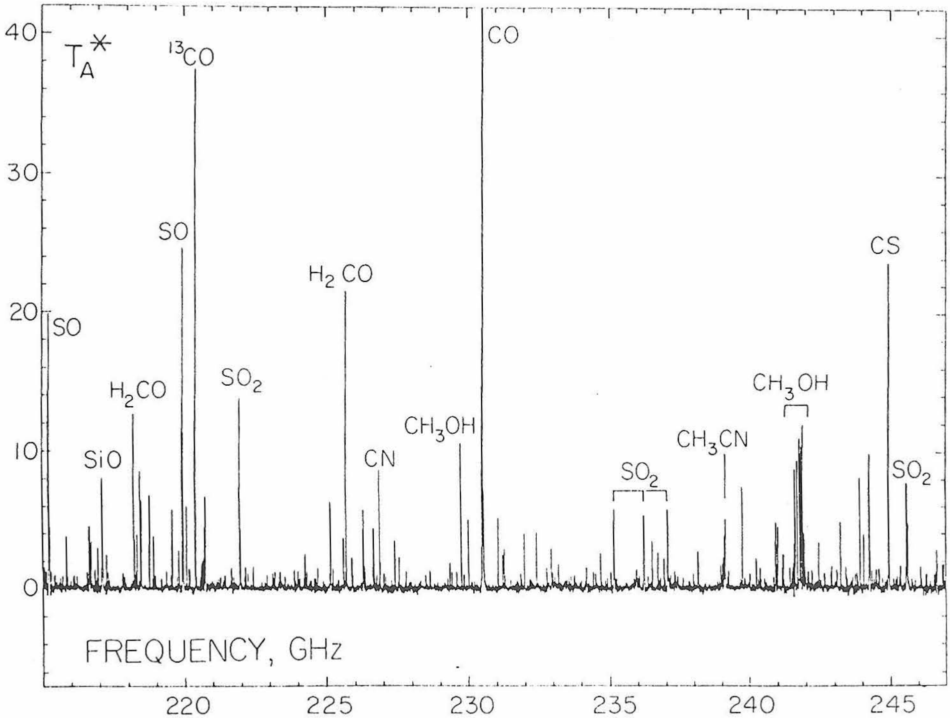

Figure 8

ATOMIC SPECTROSCOPY

The expectation that atomic fine structure lines would be useful for interstellar medium investigation used to be more widespread than the equivalent expectation for molecular rotation lines, but only recently have observations been made of the submillimeter and far-infrared atomic transitions. Table 3 gives a list of detected transitions.

Table 3

Submillimeter and Far-Infrared Atomic Fine Structure Lines

Species	Transition	Wavelength	Reference
CI	$^3P_1 - {}^3P_0$	609μm	Phillips *et al.*(1980)
	$^3P_2 - {}^3P_1$	370μm	Jaffe *et al.* (1985)
CII	$^2P_{3/2} - {}^2P_{1/2}$	158μm	Russell *et al.** (1980)
OI	$^3P_2 - {}^3P_1$	63μm	Melnick, Gull, and Harwit* (1979)
	$^3P_1 - {}^3P_0$	146μm	Stacey *et al.* (1983)b
OIII	$^3P_1 - {}^3P_0$	88μm	Ward *et al.* (1975)
	$^3P_2 - {}^3P_1$	52μm	Melnick, *et al.* (1978)
NIII	$^2P_{3/2} - {}^2P_{1/2}$	57μm	Watson *et al* (1981)

(1) CI

Atomic carbon is one of the most suitable constituents to monitor in order to learn about the properties of the interstellar medium. It is widespread and has energy levels which are reasonably well populated at the typical gas temperatures. The $^3P_1$ - $^3P_0$ transition, by chance, has a similar Einstein A coefficient and collision cross section to that of CO (J = 1-0), so that these two basic transitions of the dense gas can be usefully compared. CI has been detected from the KAO, with the InSb heterodyne receiver, in the 609μm line and has been found to permeate the entire dense interstellar medium, with column densities approaching those of CO (Phillips and Huggins, 1981). This unexpected result has caused a revival of interest in chemical and physical models of the interstellar gas, and among the new suggestions is that of Langer et al. (1984), which is that the abundance of C may be greater than that of O in the dense clouds! Figure 9 shows a set of spectra for a variety of dense molecular clouds.

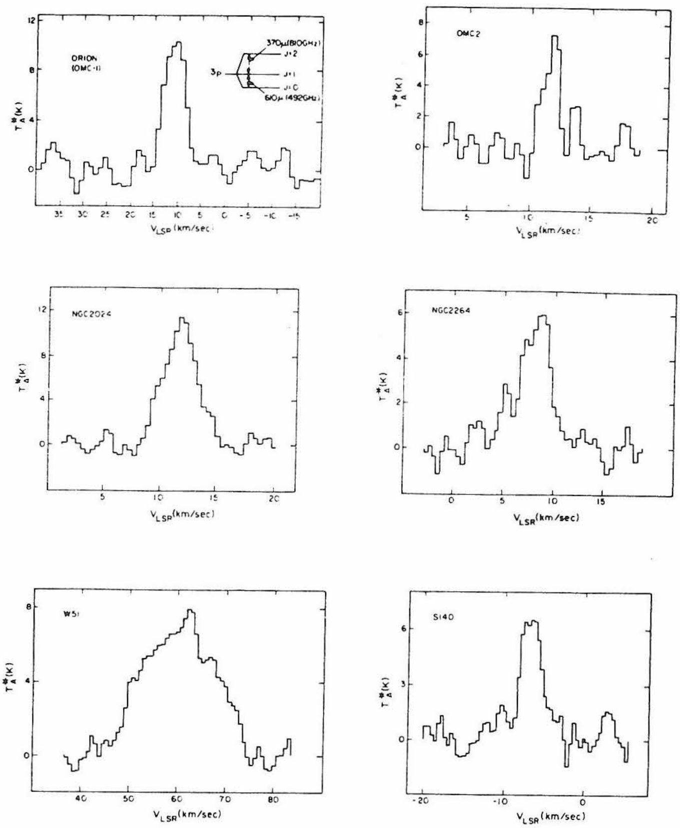

Figure 9

(2) CII

In the diffuse interstellar medium, carbon is largely in the singly ionized state. As a result, the $158\mu m$ fine structure $^2P_{3/2}$ - $^2P_{1/2}$ transition is of prime interest for cooling and possibly for defining the physics of those regions. Also, it may be observable from dense regions. It is of great use to astronomy even though the techniques for detection have only recently become available. Currently, it can be detected with both grating and Fabry-Perot instruments. Hopefully, in the future heterodyne instruments will be available to fully resolve the velocity structure. In nearby galaxies, the velocity width is greater than the Fabry-Perot spectrometer resolution, so that data can be compared with CO spectra. Figure 10 shows a set of spectra taken at various points in M82, indicating that, on the whole, the CII distribution is similar to that of CO (Crawford et al. 1984).

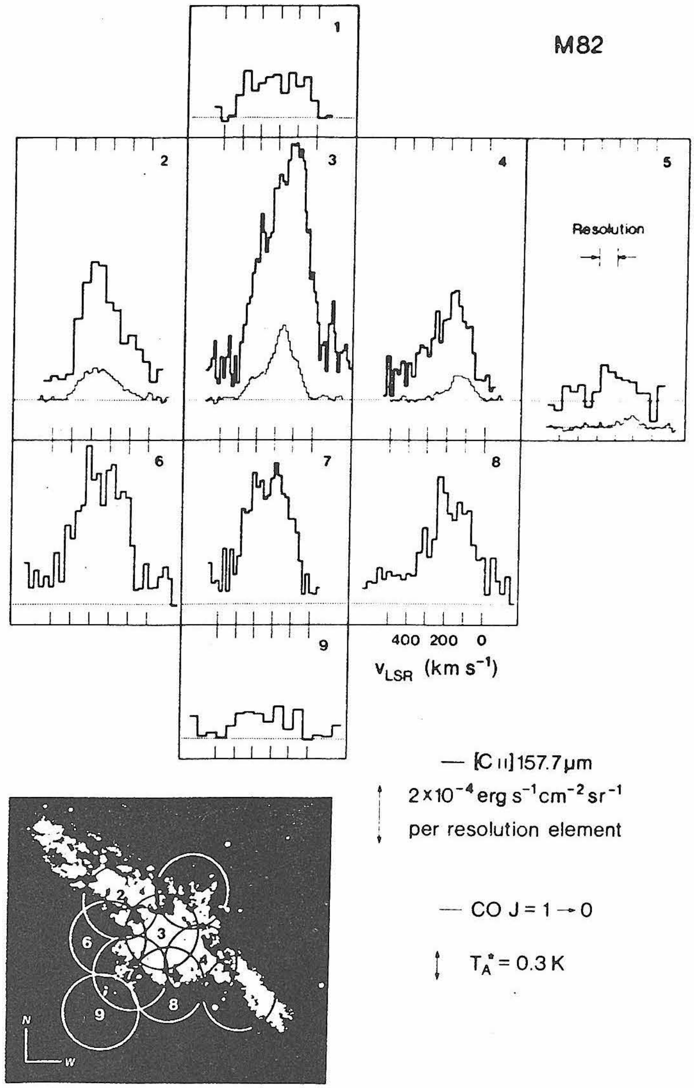

Figure 10

(3) OI, OIII and NIII

These lines together provide excellent information about the state of ionization of oxygen, the total abundance of oxygen, and the oxygen to nitrogen ratio. OI might be expected to coexist with CII in neutral diffuse regions. A considerable body of work has been performed with the oxygen lines (see e.g. Watson, 1984). Again, the nearby galaxy work is impressive where the instrumental resolution can show the structure of the line profile. Figure 11 is of the OIII $^3P_1$ - $^3P_0$ transition in M82 (Watson

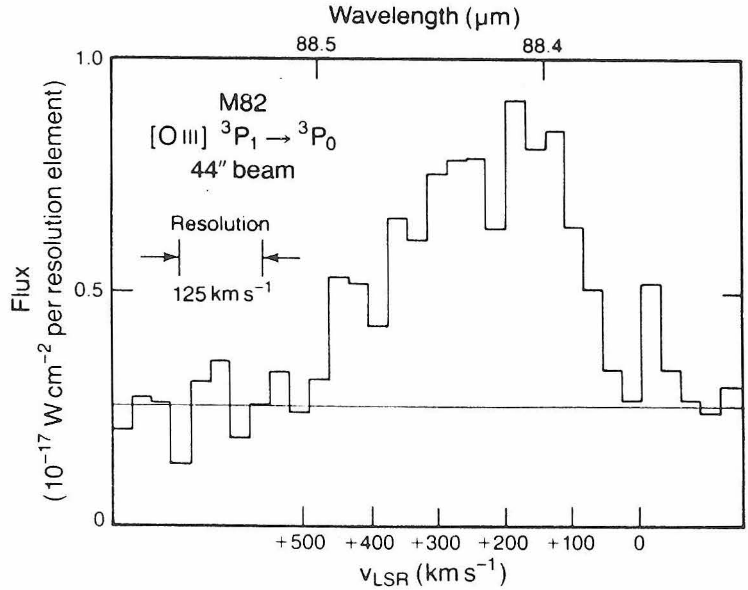

Figure 11

et. al. 1984b). A good example of the use of the OIII and NIII lines is given by Dinerstein et al. (1984), who have measured the N/O abundance ratio by observing ionized nebulae across the galaxy.

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